Cryogenic Delay Line for Far-IR Interferometry in Space

P.R. Lawson, M.R. Swain, J.D. Moore, G.L. Brack
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

1 Introduction

Direct-detection interferometry in space at far-IR/submillimeter wavelengths holds the promise of opening up an entirely new domain of astrophysical research. High angular resolution observations at wavelengths of 40-400 microns will allow us to determine the star formation rate as a function of redshift, and investigate fundamental questions relating to the history of star formation and the evolution of the universe (Swain 1998; Mather et al. 1998; Rieke et al. 1999). High angular resolution is required to avoid confusion due to the extragalactic background, with the highest resolution only being accessible through the use of long-baseline interferometry. To the authors' knowledge, no prior technology development has addressed the problems of direct-detection far-IR interferometry in space. At these wavelengths cryogenic optical systems are required, augmented with the active servo systems necessary for interferometry. One of the most challenging and crucial components of an interferometer is its delay line. We have designed and assembled a prototype cryogenic delay line to provide delays of up to 0.5 m that we are now in the process of testing. Its design, current status, and ongoing development will be described.

2 Design Requirements for Far-IR Interferometry

Although two missions studies for far-IR space interferometry, SPIRIT and SPECS, are presently being developed at NASA's Jet Propulsion Laboratory and Goddard Space Flight Center (Shao et al. 2000; Leisawitz et al. 2000), no direct detection long-baseline interferometer has ever previously been designed, let alone built, to work at wavelengths longer than about 20 microns. The longer wavelengths of the far-infrared and submillimeter require low temperature optics and extensive baffling for background limited observations. Although the optical delay line designed for the

Figure 1: The large number of axle bearings in the SIM delay line make it unsuitable for cryogenic operation.

Space Interferometry Mission (SIM) will be able to survive thermal-vacuum testing, it is unsuited for cryogenic operation because of the large number of axles and moving parts it contains. In fact the SIM breadboard design has only been tested to survive -20 to 60 C in a hard vacuum, and is only intended to operate at 10 to 30 C. An active adjustable delay line, with a stroke of more than a few cms, has yet to be demonstrated for operation in a cryogenic environment. Interferometers must typically compensate for many meters of delay path, although with a manoeuverable space interferometer this may be reduced to several tens of centimeters. The most challenging requirement of the design is therefore the need to provide a stroke of the order of 0.5 m, without using rotating axles which would potentially seize.

The motion of the delay line should not degrade the measured fringe visibility; and thus pathlength vibrations, angular fluctuations, and the lateral shear of the optical beams should be controlled. The sensitivity to each of these effects depends on the chosen design. We have adopted a movable cat's eye optical design, typical of ground-based interferometers, and have required the total visibility losses to be less than 1%. The cat's eye is similar to a retro-reflector in that its input and output beams are always parallel, but lateral motions of the cat's eye double the shear between the input and output beams. To maintain visibility losses due to shear to be less than 0.5% for a 10 cm beam implies a straightness of travel of 250 μm over the full stroke. The requirement for 0.5% loss due to jitter is 1.2 μm at a wavelength of 100 μm.

Designing and building a cryogenic delay line with a high degree of reliability is a major technological challenge. We are exploring two designs that are substantially different from the delay line being used with SIM. Our objective is to design a system without the use of axles, providing 50 cm of delay (25 cm travel), that is free from sliding friction, and that can be operated in the hard vacuum of space, down to temperatures as low as 4 K.

3 Double Porch-Swing Delay Line

The earliest design that we considered uses flexure-pivots to provide linear travel with a "double porch-swing" coupling. This concept was developed by Don Jennings at NASA GSFC for SIRIS, a balloon-born LN2-cooled FTS system operating with a 12.5 cm linear travel and shown in Fig. 2. The same concept is being considered for use in the SPIRE spectrometer on FIRST. We are scaling the design to provide a 25 cm travel and to accommodate our optics. We will test the rigidity and vibration characteristics as well
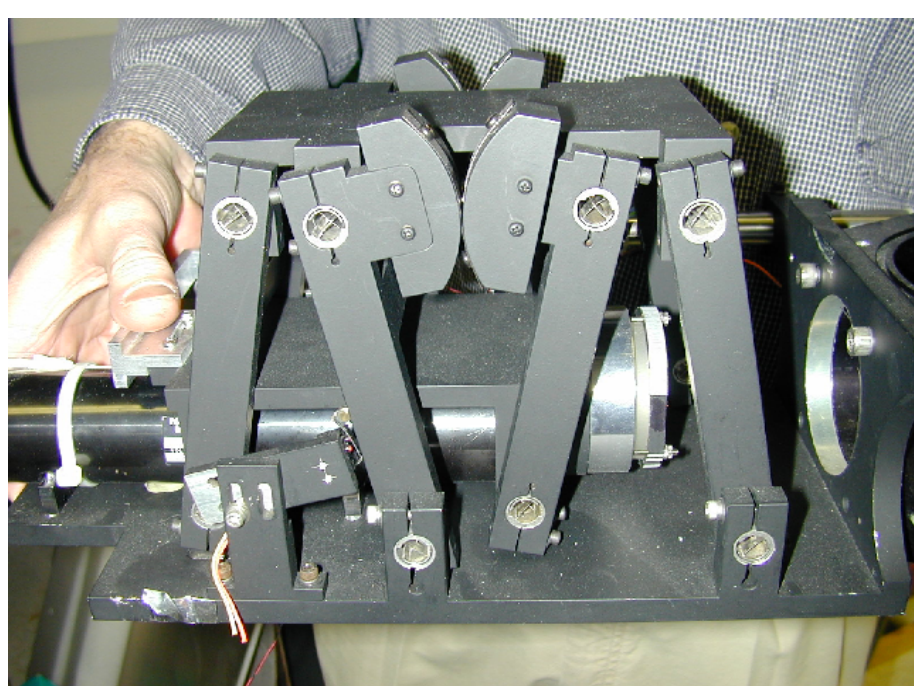
Figure 2: Double-porch-swing carriage from SIRIS using flexure pivots (Courtesy of D.E. Jennings, GSFC).

as the expected aging of the flexure pivots. This prototype is being manufactured at NASA Goddard for delivery and testing at JPL.
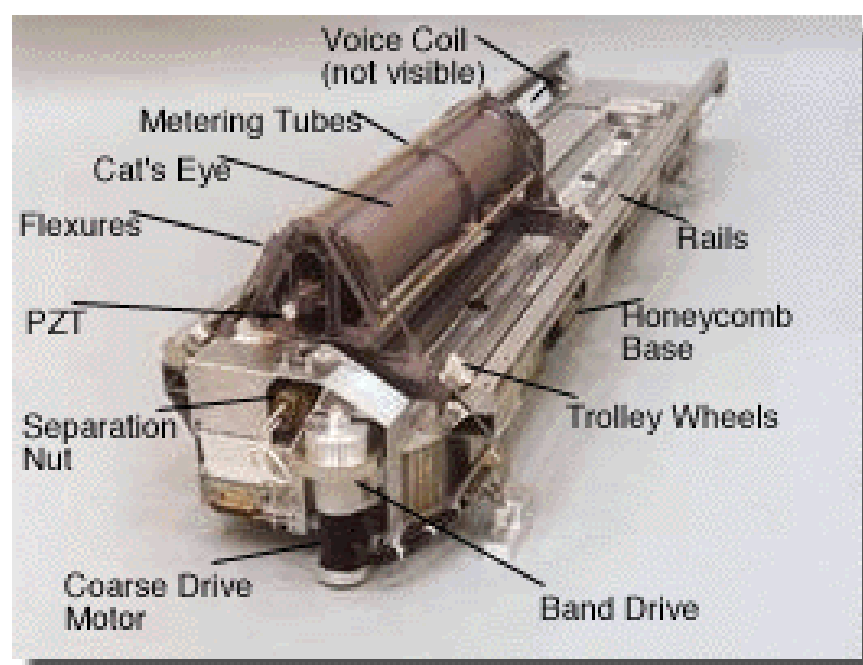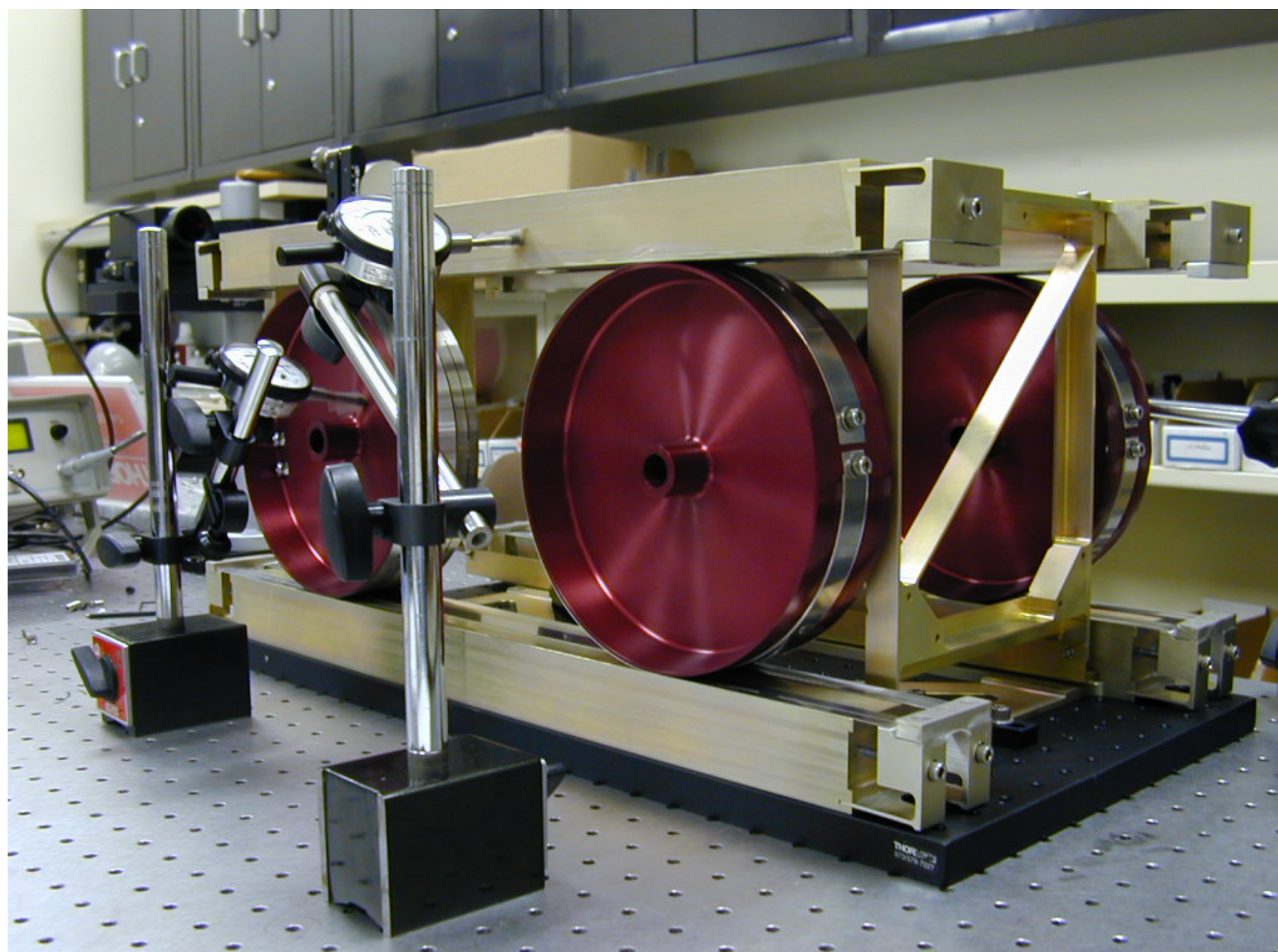

Figure 3: Cryogenic delay line with wheels constrained by straps. The upper platform supports the optics and rolls along the top of the wheels.
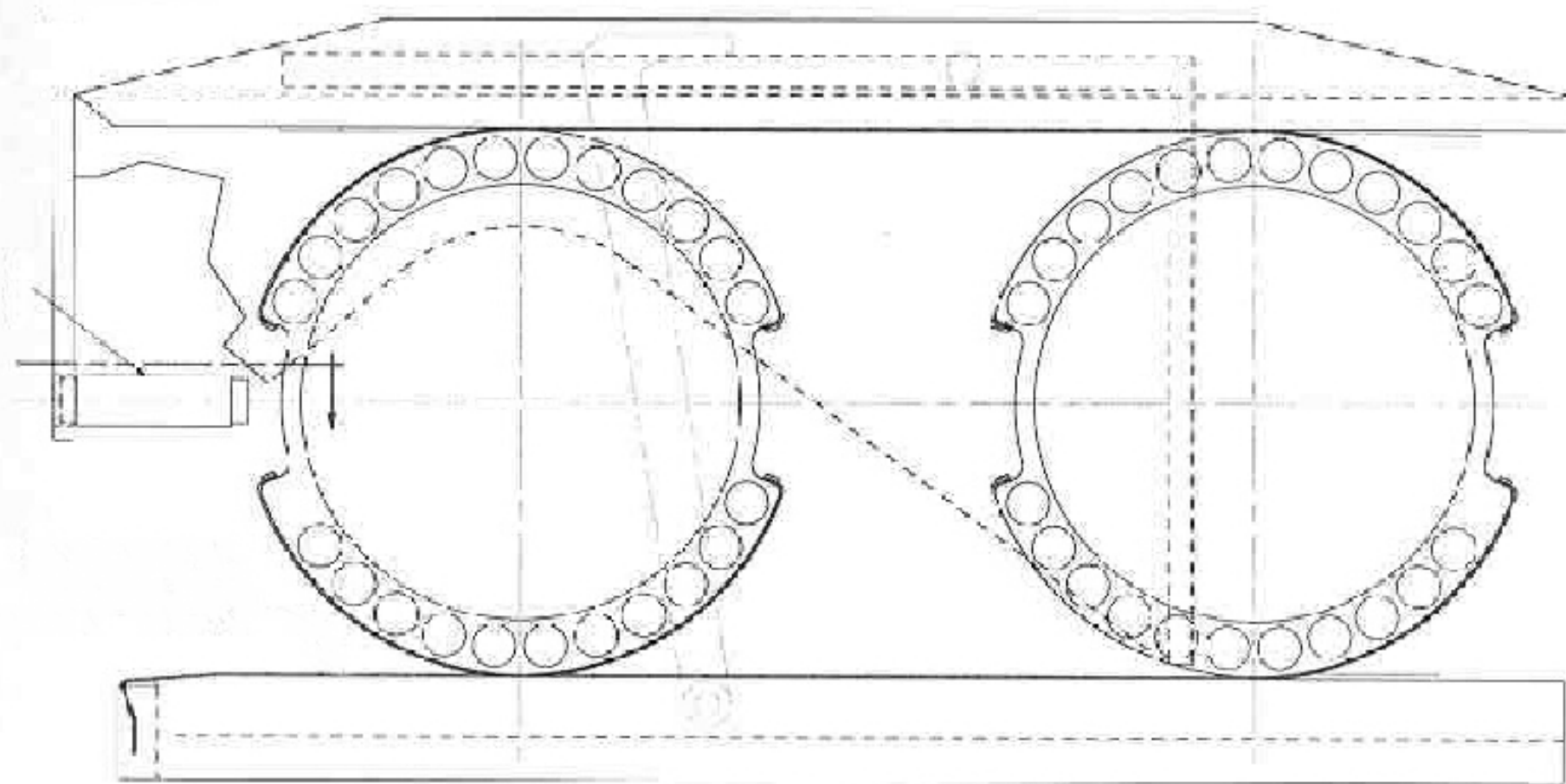

Figure 4: Early conceptual drawing of strapped-wheel delay line design.

4 Strapped-Wheel Delay Line

Because of concerns about the complexity and rigidity of the double porch-swing design, we have in parallel developed an entirely new design as shown in the photograph of Fig. 3 and the conceptual drawing of Fig. 4. The principle of operation is very simple: an upper platform rides on top of the wheels, and from the platform are suspended the optics of the delay line. By rolling the platform across the wheels the optics can be moved back and forth in a straight line, as illustrated in Fig. 5. There are no axles in this system; the wheels are constrained only by straps.
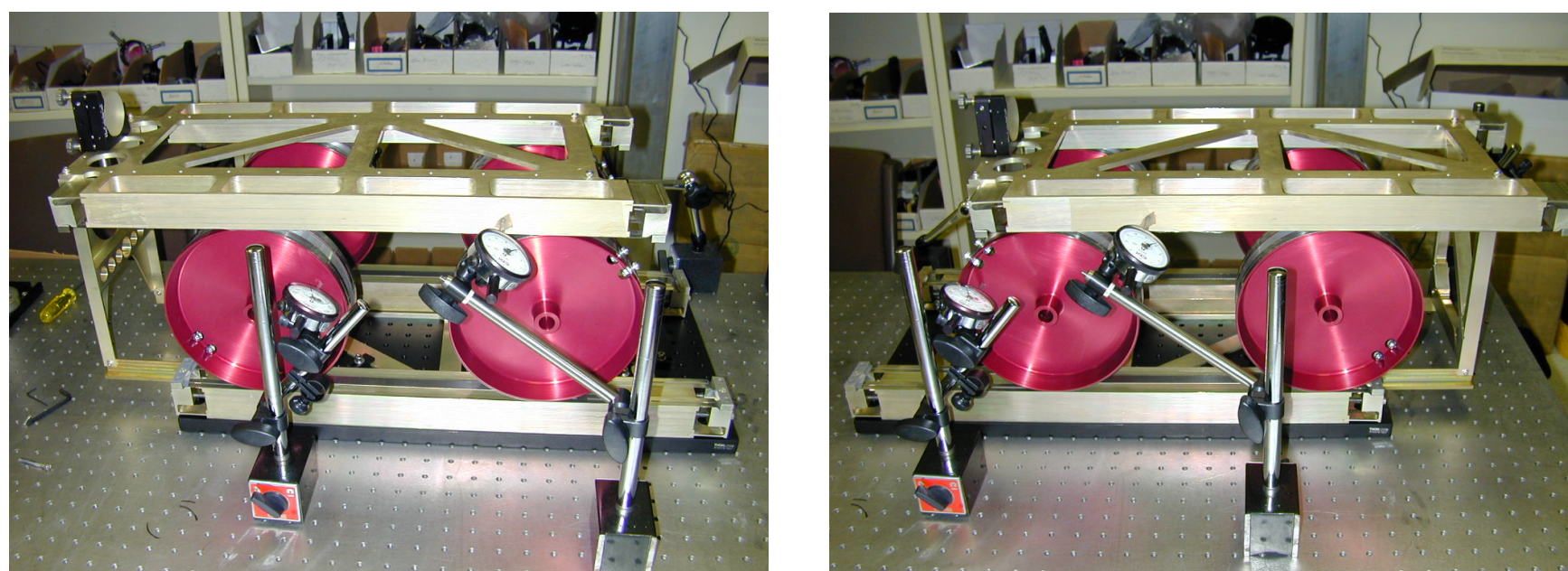

Figure 5: Left and right motions of carriage.

In our design each wheel has three straps, visible in Fig. 6. Two outer straps are launched at the end of the bottom stage, pass underneath the wheel, on the left and right rim, and terminate on the end of the upper stage above where they were launched. For each pair of wheels on the left and right-hand side of the carriage there is also a strap that binds the pair together as a unit, passing around the outside circumference

Figure 6: View showing wheel straps.

of the pair and so setting the wheel separation. The alignment of the wheels is tuned by adjusting the tension in the outer strap launchers. The carriage is manufactured entirely from aluminum with the exception of the the stainless-steel straps and the magnetic preload. The preload comprises 24 Neodymium Iron Boron magnets (0.5-inch in diameter) inserted in counterbores within the aluminum base, and which clamp (across an air gap) onto left and right iron rails suspended from the upper platform. This provides remarkable rigidity. The carriage has been tuned for a runout of 25 μm over its full travel—a factor of 10 better than our requirement.
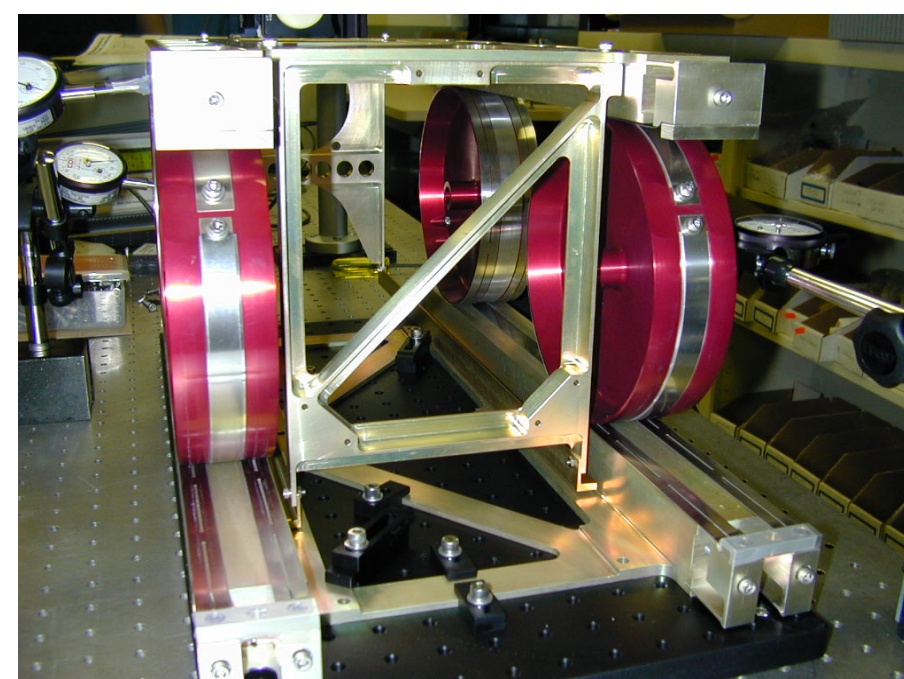
5 Cat's Eye Optical Design

Long delay lines used for ground-based stellar interferometry typically use a cat's eye design similar to the one depicted in Fig. 7. Collimated input beams arrive parallel but to one side of the optical axis of a parabolic mirror, are focused to a flat mirror, and are then re-collimated and output on the opposite side of the axis, parallel to the input beam.

Figure 7: Typical delay line design for ground-based optical interferometers (Shao et al. 1988)

This design allows rapid pathlength corrections to be introduced by a small piezo-driven flat mirror at the focus of the parabola.
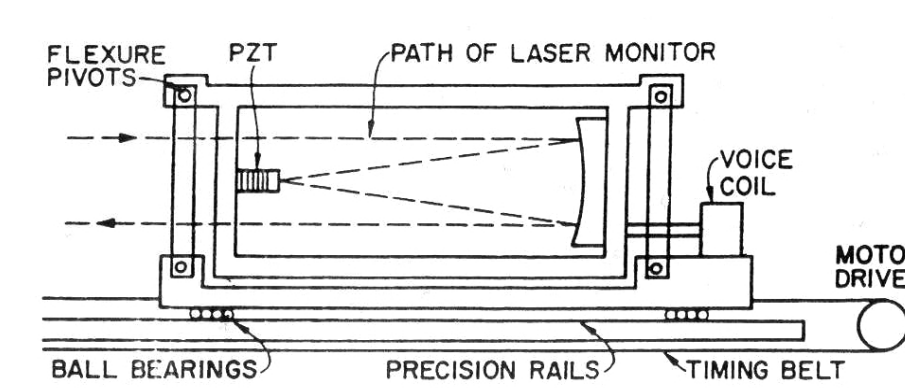
Our design is sized to accommodate 10 cm diameter beams at a wavelength of 100 μm, yielding a Fresnel number of 10 at a distance of 2.5 m. The parabolic mirror is 123 $\times$ 254 mm with a 381 mm focal length, manufactured by Axsys Technologies as a lightweighted diamond-turned 6061-T6 aluminum mirror with a surface expected to be 0.25–0.50 waves peak-to-peak (HeNe) over the 10 cm subapertures. This will provide a $\lambda/30$ surface at a wavelength of 10 μm, where preliminary tests will be conducted.

6 Metrology and Control System

The metrology and servo control system for the delay line is being implemented using Pentium III PCs running RTLinux, modelled after the control system of the CHARA Array (ten Brummelaar 2000). A pathlength-control servo loop with a bandwidth of 2 kHz will be adequate to control the jitter and easily obtainable using PC-based hardware and hard real time software. The delay will be monitored with a Zygo ZMI-2000 metrology system with a compact single-beam interferometer and PC measurement board, providing a resolution of 0.6 nm, position range of ±21.2 m, a maximum velocity of 4.2 m/s, and a readout rate of 60 kHz.

A two-stage servo will be implemented comprising the piezo transducer on the cat's eye assembly, and a cryogenic stepper motor. The stepper motor is a Phytron VSS 42 model, with 500 steps/rev and a 20:1 gear reduction. Used with a 3.0 cm diameter spindle it provides 0.47 μm/step in microstep mode and 9.4 μm/step in full-step mode, allowing the full range of travel to be scanned in 26 seconds. The piezo actuator is a custom Physics Instrumente HVPZ-239 model, with sub-nm resolution and mounted to provide a full-wavelength stroke at λ=100 μm.

7 Current Status and Future Plans

The strapped-wheel delay line prototype is largely complete, and initial mechanical tests have shown it able to meet or exceed our requirements. We are currently awaiting delivery of the parabolic mirror of the cat's eye and parts to complete the piezo actuator for testing. Work is underway to integrate the metrology within the control system. When this work is complete we will evaluate the warm performance of the double porch-swing and strapped-wheel designs and choose only 1 design for the cryogenic tests which will follow later this year.

As part of our long-term goal of developing a fully operational testbed for far-IR space interferometry, we will design and build a background-limited far-IR beam combiner. As illustrated in Fig. 8, microwave components can be laser micromachined for use at 2 THz (λ=150 μm), and in principle structures for wavelengths as short at 60 μm may be made (Walker et al. 1998). In collaboration with Chris Walker and his group we will design and test the basic waveguide components for λ=100 μm, including magic tees and directional couplers, and proceed to design and build a three and four-input beam combiner for direct detection synthesis

Figure 8: Laser machined waveguide structures, will be used to build a single-mode direct-detection beam combiner for λ=100 μm. (Courtesy of Chris Walker, Steward Observatory)

imaging, similar to the single-mode fiber and integrated optics combiners of FLUOR (Coudé du Foresto et al. 1998) and IONIC (Malbet et al. 1999).
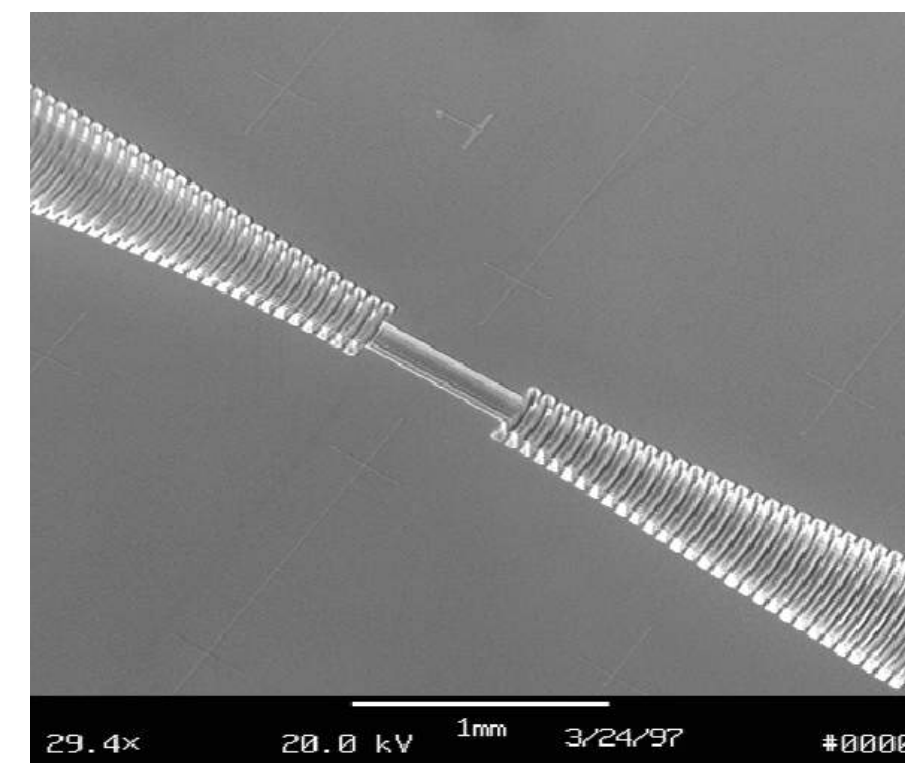
See the related Poster 14.09.

References:
T.A. ten Brummelaar 2000, Proc. SPIE 4006, 564; V. Coudé du Foresto et al. 1998, Proc. SPIE 3350, 856; D.T. Leisawitz et al. 2000, Proc. SPIE 4013, 36; F. Malbet et al. 1999, Astron. Astrophys. 138, 135; J.C. Mather et al. 1998, http://www.gsfc.nasa.gov/astro/specs/specs_3_7.pdf; G.H. Rieke et al. 1999, http://mips.as.arizona.edu/MIPS/fircase3.pdf; M. Shao et al. 1988, Astron. Astrophys. 193, 357; M. Shao et al. 2000, Proc. SPIE 4006, 772; M.R. Swain 1998, Pub. Astron. Soc. Pac. 110, 991; C.K. Walker et al. 1998, Proc. SPIE 3357, 45.